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(54) **DATA STORAGE DEVICE COMPRISING TWO-DIMENSIONAL DATA DEPENDENT NOISE WHITENING FILTERS FOR TWO-DIMENSIONAL RECORDING**

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None
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(57) **ABSTRACT**

A data storage device is disclosed wherein a first 2D data dependent noise whitening (DDNW) filter is configured to perform 2D DDNW of first and second 2D equalized samples to generate first 2D noise whitened samples. A second 2D DDNW filter is configured to perform 2D DDNW of the first and second 2D equalized samples to generate second 2D noise whitened samples. A 2D sequence detector is configured to detect a first data sequence recorded in a first data track from the first and second 2D noise whitened samples and to detect a second data sequence recorded in a second data track from the first and second 2D noise whitened samples.

26 Claims, 3 Drawing Sheets

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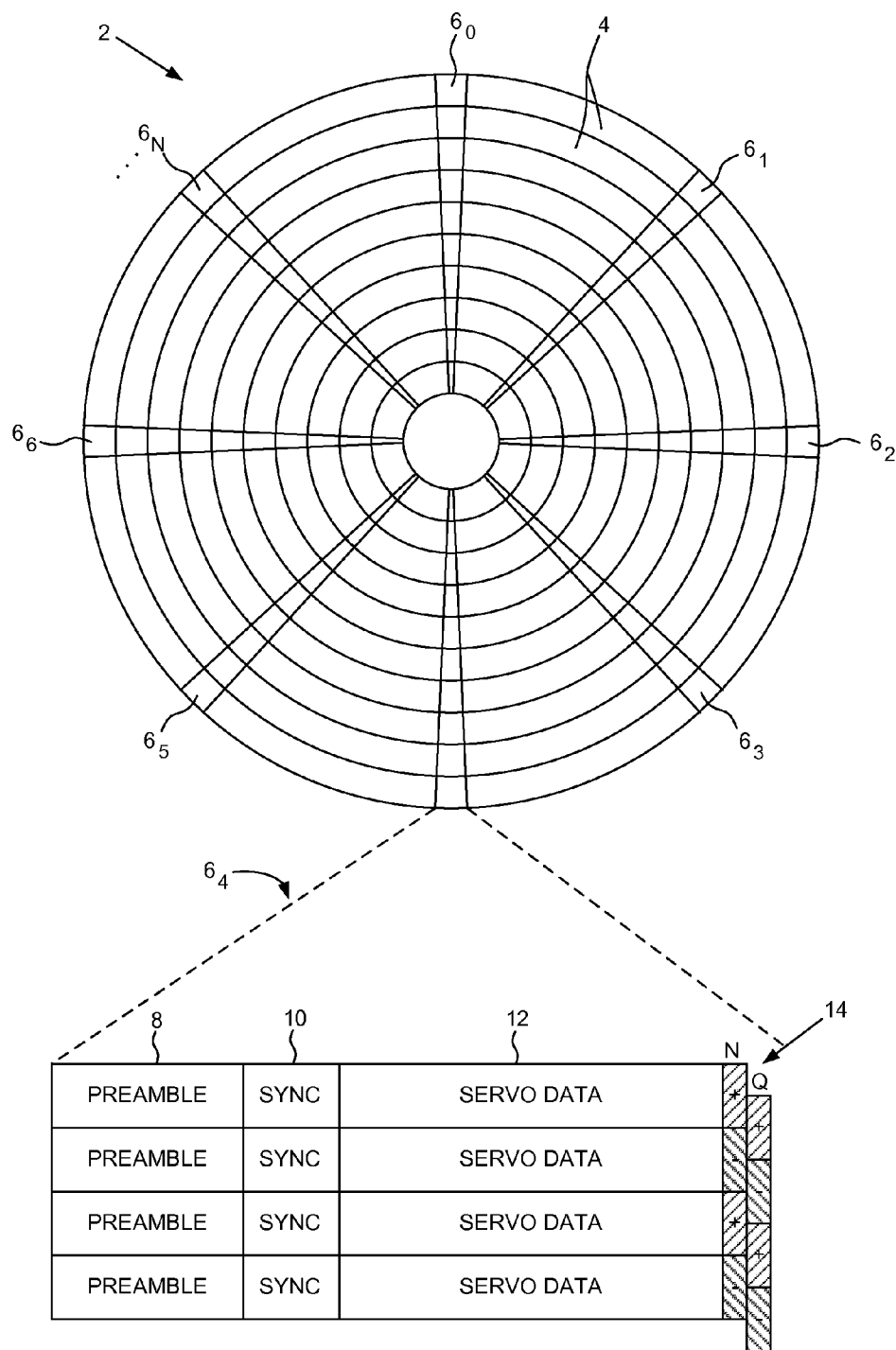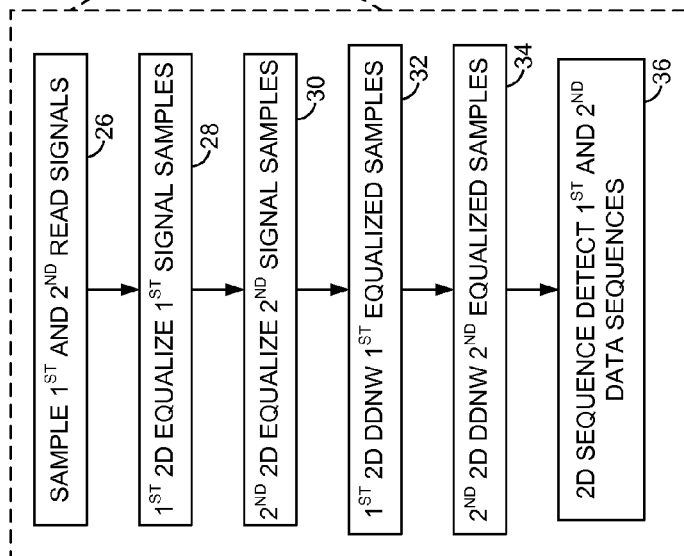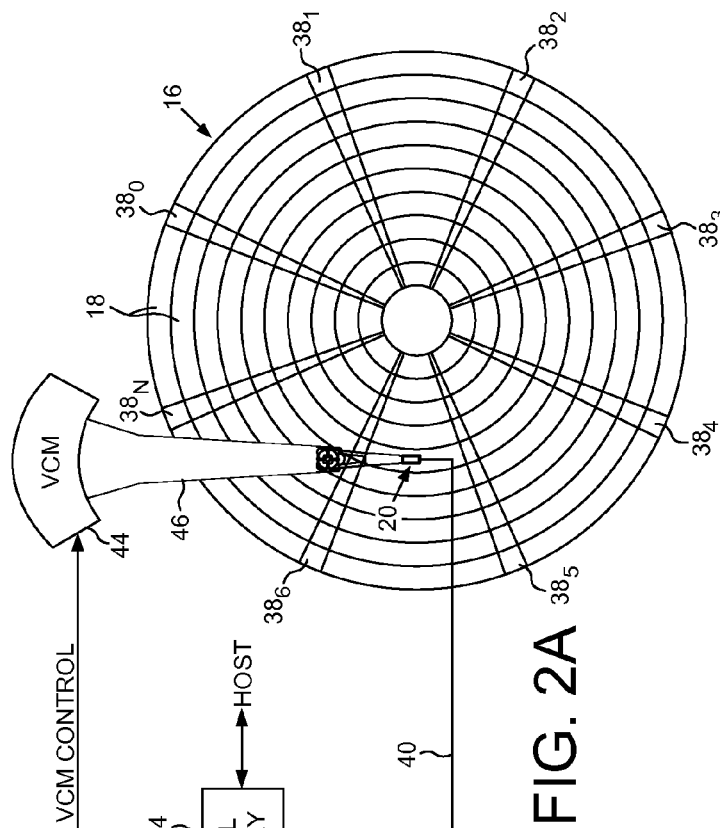
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PREAMBLE	SYNC	SERVO DATA	N	Q
PREAMBLE	SYNC	SERVO DATA		
PREAMBLE	SYNC	SERVO DATA		
PREAMBLE	SYNC	SERVO DATA		

FIG. 1

(Prior Art)

FIG. 2A

FIG. 2B

SAMPLE 1ST AND 2ND READ SIGNALS — 26

1ST 2D EQUALIZE 1ST SIGNAL SAMPLES — 28

2ND 2D EQUALIZE 2ND SIGNAL SAMPLES — 30

1ST 2D DDNW 1ST EQUALIZED SAMPLES — 32

2ND 2D DDNW 2ND EQUALIZED SAMPLES — 34

2D SEQUENCE DETECT 1ST AND 2ND DATA SEQUENCES — 36
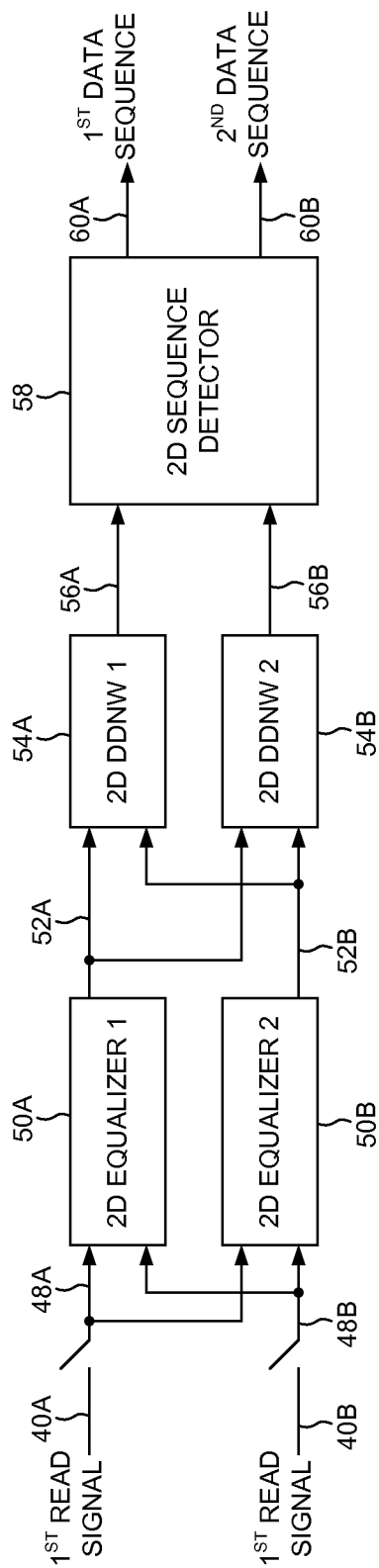
FIG. 2C

FIG. 3

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DATA STORAGE DEVICE COMPRISING TWO-DIMENSIONAL DATA DEPENDENT NOISE WHITENING FILTERS FOR TWO-DIMENSIONAL RECORDING

BACKGROUND

Data storage devices such as disk drives comprise a disk and a head connected to a distal end of an actuator arm which is rotated about a pivot by a voice coil motor (VCM) to position the head radially over the disk. The disk comprises a plurality of radially spaced, concentric tracks for recording user data sectors and servo sectors. The servo sectors comprise head positioning information (e.g., a track address) which is read by the head and processed by a servo control system to control the actuator arm as it seeks from track to track.

FIG. 1 shows a prior art disk format 2 as comprising a number of servo tracks 4 defined by servo sectors 6_0-6_N, wherein data tracks are defined relative to the servo tracks 4. Each servo sector 6_i comprises a preamble 8 for storing a periodic pattern, which allows proper gain adjustment and timing synchronization of the read signal, and a sync mark 10 for storing a special pattern used to symbol synchronize to a servo data field 12. The servo data field 12 stores coarse head positioning information, such as a servo track address, used to position the head over a target data track during a seek operation. Each servo sector 6_i further comprises groups of servo bursts 14 (e.g., A, B, C and D bursts), which comprise a number of consecutive transitions recorded at precise intervals and offsets with respect to a servo track centerline. The groups of servo bursts 14 provide fine head position information used for centerline tracking while accessing a data track during write/read operations.

Data is typically written to data sectors within a data track by modulating the write current of a write element, for example, using a non-return to zero (NRZ) encoding where a binary "1" is written using positive write current (+1) and a binary "0" is written using a negative write current (−1), thereby writing magnetic transitions onto the disk surface. A read element (e.g., a magnetoresistive (MR) element) is then used to transduce the magnetic transitions into a read signal that is demodulated by a read channel. The recording and reproduction process may be considered a communication channel, wherein communication demodulation techniques may be employed to demodulate the read signal.

A common demodulation technique employed in disk drives is known as partial response maximum likelihood (PRML), wherein the recording channel is equalized into a desired partial response (e.g., PR4, EPR4, etc.), the resulting read signal sampled, and the signal samples demodulated using a ML data detector. The ML data detector is commonly implemented using the well known Viterbi data detector which attempts to find the minimum distance sequence (in Euclidean space) through a trellis. The accuracy of a Viterbi data detector matches a true ML data detector only if the signal noise is time invariant (data independent) and white (statistically independent) with a Gaussian probability distribution.

In the magnetic recording channel of a disk drive, the signal noise is neither data independent nor white, and therefore signal processing techniques have been employed to improve the accuracy of the ML data detector by compensating for the data dependent, non-white noise in the read signal. For example, the prior art has employed a bank of data dependent noise whitening filters in front of the ML detector that each attempt to whiten the signal noise based on an optimal noise-

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whitening function for each possible recorded data sequence. The output of each data dependent noise whitening filter is then used to compute the corresponding branch metrics in the ML detector (e.g., for each branch corresponding to the data sequence assigned to each data dependent noise whitening filter). Since the noise correlating effect of the recording channel (including the equalizer filter) is essentially infinite, the performance of each data dependent noise whitening filter increases as the length of the corresponding data sequence increases. However, the number of data dependent noise whitening filters also doubles with each additional bit in the data sequence (e.g., there are 2^N data dependent noise whitening filters where N is the length of the data sequence).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a prior art disk format comprising a plurality of servo tracks defined by servo sectors.

FIG. 2A shows a data storage device in the form of a disk drive according to an embodiment comprising a head actuated over a disk comprising a plurality of data tracks.

FIG. 2B shows an embodiment wherein the head comprises a first read element positioned over a first data track, and a second read element positioned over a second data track.

FIG. 2C is a flow diagram according to an embodiment wherein two-dimensional (2D) data dependent noise whitening (DDNW) filtering is employed to detect data sequences recorded in the first and second tracks.

FIG. 3 shows control circuitry according to an embodiment comprising 2D equalizers, 2D DDNW filters, and a 2D sequence detector.

DETAILED DESCRIPTION

FIG. 2A shows a data storage device comprising a disk 16 comprising a plurality of data tracks 18, and a head 20 actuated over the disk 16, wherein the head 20 comprises a first read element 22A and a second read element 22B (FIG. 2B). The disk drive further comprises control circuitry 24 configured to execute the flow diagram of FIG. 2C, wherein the first read element 22A is positioned over a first data track k−1 and the second read element 22B is positioned over a second data track k as shown in FIG. 2B. A first read signal from the first read element is sampled to generate first signal samples, and a second read signal from the second read element is sampled to generate second signal samples (block 26). First two-dimensional (2D) equalization is performed on the first signal samples and the second signal samples to generate first 2D equalized samples (block 28), and a second 2D equalization is performed on the first signal samples and the second signal samples to generate second 2D equalized samples (block 30). First 2D data dependent noise whitening (DDNW) filtering is performed on the first and second 2D equalized samples to generate first 2D noise whitened samples (block 32), and second 2D DDNW filtering is performed on the first and second 2D equalized samples to generate second 2D noise whitened samples (block 34). A first data sequence recorded in the first data track is detected from the first and second 2D noise whitened samples and a second data sequence recorded in the second data track is detected from the first and second 2D noise whitened samples (block 36).

In the embodiment of FIG. 2A, the disk 16 comprises a plurality of servo sectors 38_0-38_N that define a plurality of servo tracks, wherein the data tracks 18 are defined relative to the servo tracks at the same or different radial density. The control circuitry 24 processes a read signal 40 emanating

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from the head 20 to demodulate the servo sectors 38_0-38_N and generate a position error signal (PES) representing an error between the actual position of the head and a target position relative to a target track. The control circuitry 24 filters the PES using a suitable compensation filter to generate a control signal 42 applied to a voice coil motor (VCM) 44 which rotates an actuator arm 46 about a pivot in order to actuate the head 20 radially over the disk 16 in a direction that reduces the PES. The servo sectors 38_0-38_N may comprise any suitable head position information, such as a track address for coarse positioning and servo bursts for fine positioning. The servo bursts may comprise any suitable pattern, such as an amplitude based servo pattern or a phase based servo pattern.

FIG. 3 shows control circuitry according to an embodiment wherein a first read signal 40A emanating from the first read element 22A (FIG. 2B) is sampled to generate first signal samples 48A, and a second read signal 40B emanating from the second read element 22B is sampled to generate second signal samples 48B. A first 2D equalizer 50A performs 2D equalization on the first and second signal samples 48A and 48B to generate first 2D equalized samples 52A, and a second 2D equalizer 50B performs 2D equalization on the first and second signal samples 48A and 48B to generate second 2D equalized samples 52B. In one embodiment, the first 2D equalizer 50A performs 2D equalization based on a target response of the data recorded in the first data track k−1 (FIG. 2B), and the second 2D equalizer 50B performs 2D equalization based on a target response of the data recorded in the second data track k. That is, the first 2D equalized samples 52A are samples that correspond to data recorded in the first data track k−1 including the effect of intersymbol interference (ISI) from the first data track k−1 as well as ISI from data recorded in the second data track k. Similarly, the second 2D equalized samples 52B are samples that correspond to data recorded in the second data track k including the effect of ISI from the second data track k as well as ISI from data recorded in the first data track k−1.

A first 2D DDNW filter 54A performs data dependent noise whitening on the first and second 2D equalized samples 52A and 52B to generate first 2D noise whitened samples 56A, and a second 2D DDNW filter 54B performs data dependent noise whitening on the first and second 2D equalized samples 52A and 52B to generate second 2D noise whitened samples 56B. A 2D sequence detector 58 is configured to detect a first data sequence 60A recorded in the first data track from the first and second 2D noise whitened samples 56A and 56B and to detect a second data sequence 60B recorded in the second data track from the first and second 2D noise whitened samples 56A and 56B.

Any suitable 2D equalizer may be employed in FIG. 3 as well as any suitable 2D sequence detector 58, such as a suitable 2D Viterbi detector. The details of the 2D equalization and sequence detection algorithms are omitted from this disclosure for clarity. The following is a detailed derivation for embodiments of the 2D DDNW filters 54A and 54B of FIG. 3, as well as an embodiment for computing the branch metrics of the sequence detector 58 based on the predicted error sequences.

In one embodiment, the first 2D DDNW filter 54A is configured to minimize a first data dependent noise prediction error $e_{k-1,t}(b)$ based on:

$$e_{k-1,t}(b) = n_{k-1,t}(b) - A_1^T(b)n(b) - m_1(b)$$

and the second 2D DDNW filter 54B is configured to minimize a second data dependent noise prediction error $e_{k,t}(b)$ based on:

$$e_{k,t}(b) = n_{k,t}(b) - A_2^T(b)n(b) - m_2(b)$$

where t represents a time index, b represents one of a plurality of data patterns, n(b) represents a 2D vector of past noise samples in the first and second 2D equalized samples 52A and 52B, $n_{k-1,t}(b)$ represents a noise sample in the first equalized samples 52A, $A_1(b)$ represents a first data dependent noise prediction filter, $m_1(b)$ represents a DC component of predicted noise in the first 2D equalized samples 52A, $n_{k,t}(b)$ represents a noise sample in the second 2D equalized samples 52B, $A_2(b)$ represents a second data dependent noise prediction filter, and $m_2(b)$ represents a DC component of predicted noise in the second 2D equalized samples 52B.

In one embodiment, a goal may be to minimize the variance of the prediction errors by minimizing the expectation of the squared prediction errors $e_{k-1,t}(b)$ and $e_{k,t}(b)$:

$$E(e_{k-1,t}^2(b)) = E(n_{k-1,t}^2(b)) + A_1^T(b)R(b)A_1(b) + m_1^2(b) - 2E(n_{k-1,t}(b)n^T(b))A_1^T(b) - 2m_1(b)E(n_{k-1,t}(b)) + 2A_1^T(b)m_1(b)E(n(b))$$

$$E(e_{k,t}^2(b)) = E(n_{k,t}^2(b)) + A_2^T(b)R(b)A_2(b) + m_2^2(b) - 2E(n_{k,t}(b)n^T(b))A_2^T(b) - 2m_2(b)E(n_{k,t}(b)) + 2A_2^T(b)m_2(b)E(n(b))$$

where $R(b) = E(n(b)n^T(b))$. By taking the derivative of the above squared prediction error $e_{k-1,t}(b)$ with respect to $A_1(b)$ and $m_1(b)$ and setting the result equal to zero gives:

$$R(b)A_1(b) - E(n(b)n_{k-1,t}(b)) + m_1(b)E(n(b)) = 0$$

$$m_1(b) - E(n_{k-1,t}(b)) + A_1^T(b)E(n(b)) = 0$$

The solutions to the above equations give the optimal values for $A_1(b)$ and $m_1(b)$:

$$m_1(b) = [E(n_{k-1,t}(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n(b))][1 - E^T(n(b))R^{-1}(b)E(n(b))]^{-1}$$

$$A_1(b) = R^1(b)[E(n_{k-1,t}(b)n(b)) - m_1(b)E(n(b))]$$

where the corresponding error variance is

$$\sigma_1^2(b) = E(n_{k-1,t}^2(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n_{k-1,t}(b)n(b)) - \frac{[E(n_{k-1,t}(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n(b))]^2}{1 - E^T(n(b))R^{-1}(b)E(n(b))}$$

By taking the derivative of the above squared prediction error $e_{k,t}(b)$ with respect to $A_2(b)$ and $m_2(b)$ and setting the result equal to zero provides the following solutions for $A_2(b)$ and $m_2(b)$

$$m_2(b) = [E(n_{k,t}(b)) - E^T(n_{k,t}(b)n(b))R^{-1}(b)E(n(b))][1 - E^T(n(b))R^{-1}(b)E(n(b))]^{-1}$$

$$A_2(b) = R^1(b)[E(n_{k,t}(b)n(b)) - m_2(b)E(n(b))]$$

where the corresponding error variance is

$$\sigma_1^2(b) = E(n_{k-1,t}^2(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n_{k-1,t}(b)n(b)) - \frac{[E(n_{k-1,t}(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n(b))]^2}{1 - E^T(n(b))R^{-1}(b)E(n(b))}$$

In one embodiment, with the above defined DDNW filter banks and the corresponding DC components, the two predicted errors at the same time index $e_{k-1,t}(b)$ and $e_{k,t}(b)$ may still be correlated with each other. Accordingly, in one embodiment it may be necessary to consider their covariance matrix when computing the branch metric in the 2D sequence detector 58, where the covariance matrix may be of the form:

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$$\Sigma(b) = \begin{bmatrix} \sigma_1^2(b) & E(e_{k-1,t}(b)e_{k,t}(b)) \\ E(e_{k,t}(b)e_{k-1,t}(b)) & \sigma_2^2(b) \end{bmatrix}$$

In one embodiment, the branch metric br of the 2D sequence detector **58** may therefore be generated based on:

$$br = -1n(|\Sigma(b)|) - e_t^T \Sigma^{-1}(b) \mathrm{i} \, e_t$$

where $e_t = [e_{k-1,t}(b), e_{k,t}(b)]^T$.

In an alternative embodiment, the first 2D DDNW filter **54A** may be configured to minimize a first data dependent noise prediction error $e_{k-1,t}(b)$ based on:

$$e_{k-1,t}(b) = n_{k-1,t}(b) - \overline{A}_1^T(b)\overline{n}(b) - m_1(b)$$

and the second 2D DDNW filter **54B** may be configured to minimize a second data dependent noise prediction error $e_{k,t}(b)$ based on:

$$e_{k,t}(b) = n_{k,t}(b) - \overline{A}_2^T(b)\overline{n}(b) - m_2(b)$$

where:
$\overline{n}(b) = [n(b), 1]$;
$\overline{A}_1(b) = [A_1(b), m_1(b)]$; and
$\overline{A}_2(b) = [A_2(b), m_2(b)]$.

In this embodiment, the DC component of the predicted noise may be considered as a coefficient of the DDNW filters and the predicted error variances may be expressed as:

$$E(e_{k-1,t}^2(b)) = E(n_{k-1,t}^2(b)) - 2E(n_{k-1,t}(b)\overline{n}^T(b))\overline{A}_1(b) + \overline{A}_1^T(b)\overline{R}(b)\overline{A}_1(b)$$

$$E(e_{k,t}^2(b)) = E(n_{k,t}^2(b)) - 2E(n_{k,t}(b)\overline{n}^T(b))\overline{A}_2(b) + \overline{A}_2^T(b)\overline{R}(b)\overline{A}_2(b)$$

where $\overline{R}(b) = E(\overline{n}(b)\overline{n}^T(b))$. By taking the derivative of the first equation with respect to $\overline{A}_1(b)$ and setting the result equal to zero gives:

$$\overline{A}_1(b) = \overline{R}^{-1}(b)E(n_{k-1}(b)\overline{n}(b))$$

with a corresponding predicted error variance:

$$\sigma_1^2(b) = E(n_{k-1,t}^2(b)) - E^T(n_{k-1,t}(b)\overline{n}(b))\overline{R}^{-1}(b)E(n_{k-1,t}(b)\overline{n}(b))$$

By taking the derivative of the second equation with respect to $\overline{A}_2(b)$ and setting the result equal to zero gives:

$$\overline{A}_2(b) = \overline{R}^{-1}(b)E(n_k(b)\overline{n}(b))$$

with a corresponding predicted error variance:

$$\sigma_2^2(b) = E(n_{k,t}^2(b)) - E^T(n_{k,t}(b)\overline{n}(b))\overline{R}^{-1}(b)E(n_{k,t}(b)\overline{n}(b))$$

In this embodiment, the branch metric br of the 2D sequence detector **58** may be generated in the same manner as described above.

Any suitable control circuitry may be employed to implement the flow diagrams in the above embodiments, such as any suitable integrated circuit or circuits. For example, the control circuitry may be implemented within a read channel integrated circuit, or in a component separate from the read channel, such as a disk controller, or certain operations described above may be performed by a read channel and others by a disk controller. In one embodiment, the read channel and disk controller are implemented as separate integrated circuits, and in an alternative embodiment they are fabricated into a single integrated circuit or system on a chip (SOC). In addition, the control circuitry may include a suitable preamp circuit implemented as a separate integrated circuit, integrated into the read channel or disk controller circuit, or integrated into a SOC.

In one embodiment, the control circuitry comprises a microprocessor executing instructions, the instructions being operable to cause the microprocessor to perform the flow diagrams described herein. The instructions may be stored in any computer-readable medium. In one embodiment, they may be stored on a non-volatile semiconductor memory external to the microprocessor, or integrated with the microprocessor in a SOC. In another embodiment, the instructions are stored on the disk and read into a volatile semiconductor memory when the disk drive is powered on. In yet another embodiment, the control circuitry comprises suitable logic circuitry, such as state machine circuitry.

In various embodiments, a disk drive may include a magnetic disk drive, an optical disk drive, etc. In addition, while the above examples concern a disk drive, the various embodiments are not limited to a disk drive and can be applied to other data storage devices and systems, such as magnetic tape drives, solid state drives, hybrid drives, etc. In addition, some embodiments may include electronic devices such as computing devices, data server devices, media content storage devices, etc. that comprise the storage media and/or control circuitry as described above.

The various features and processes described above may be used independently of one another, or may be combined in various ways. All possible combinations and subcombinations are intended to fall within the scope of this disclosure. In addition, certain method, event or process blocks may be omitted in some implementations. The methods and processes described herein are also not limited to any particular sequence, and the blocks or states relating thereto can be performed in other sequences that are appropriate. For example, described tasks or events may be performed in an order other than that specifically disclosed, or multiple may be combined in a single block or state. The example tasks or events may be performed in serial, in parallel, or in some other manner. Tasks or events may be added to or removed from the disclosed example embodiments. The example systems and components described herein may be configured differently than described. For example, elements may be added to, removed from, or rearranged compared to the disclosed example embodiments.

While certain example embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions disclosed herein. Thus, nothing in the foregoing description is intended to imply that any particular feature, characteristic, step, module, or block is necessary or indispensable. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the embodiments disclosed herein.

What is claimed is:

1. A data storage device comprising:
a disk comprising a plurality of data tracks;
a head actuated over the disk, wherein the head comprises a first read element and a second read element; and
control circuitry operable to:
position the first read element over a first data track k−1 and position the second read element over a second data track k;
sample a first read signal from the first read element to generate first signal samples;
sample a second read signal from the second read element to generate second signal samples;

a first two-dimensional (2D) equalizer configured to perform 2D equalization of the first signal samples and the second signal samples to generate first 2D equalized samples;

a second 2D equalizer configured to perform 2D equalization of the first signal samples and the second signal samples to generate second 2D equalized samples;

a first 2D data dependent noise whitening (DDNW) filter configured to perform 2D DDNW of the first and second 2D equalized samples to generate first 2D noise whitened samples;

a second 2D DDNW filter configured to perform 2D DDNW of the first and second 2D equalized samples to generate second 2D noise whitened samples; and

a 2D sequence detector configured to detect a first data sequence recorded in the first data track from the first and second 2D noise whitened samples and to detect a second data sequence recorded in the second data track from the first and second 2D noise whitened samples.

2. The data storage device as recited in claim **1**, wherein:
the first 2D DDNW filter is configured to minimize a first data dependent noise prediction error $e_{k-1,t}(b)$ based on:

$$e_{k-1,t}(b) = n_{k-1,t}(b) - A_1^T(b)n(b) - m_1(b)$$

the second 2D DDNW filter is configured to minimize a second data dependent noise prediction error $e_{k,t}(b)$ based on:

$$e_{k,t}(b) = n_{k,t}(b) - A_2^T(b)n(b) - m_2(b)$$

where:
t represents a time index;
b represents one of a plurality of data patterns;
n(b) represents a 2D vector of past noise samples in the first and second 2D equalized samples;
$n_{k-1,t}(b)$ represents a noise sample in the first 2D equalized samples;
$A_1(b)$ represents a first data dependent noise prediction filter;
$m_1(b)$ represents a DC component of predicted noise in the first 2D equalized samples;
$n_{k,t}(b)$ represents a noise sample in the second 2D equalized samples;
$A_2(b)$ represents a second data dependent noise prediction filter; and
$m_2(b)$ represents a DC component of predicted noise in the second 2D equalized samples.

3. The data storage device as recited in claim **2**, where:

$$m_1(b) = [E(n_{k-1,t}(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n(b))]$$
$$[1 - E^T(n(b))R^{-1}(b)E(n(b))]^{-1}$$

$$A_1(b) = R^1(b)[E(n_{k-1,t}(b)n(b)) - m_1(b)E(n(b))]$$

$$R(b) = E(n(b)n^T(b)).$$

4. The data storage device as recited in claim **3**, where:

$$m_2(b) = [E(n_{k,t}(b)) - E^T(n_{k,t}(b)n(b))R^{-1}(b)E(n(b))][1 - E^T$$
$$(n(b))R^{-1}(b)E(n(b))]^{-1}$$

$$A_2(b) = R^1(b)[E(n_{k,t}(b)n(b)) - m_2(b)E(n(b))]$$

$$R(b) = E(n(b)n^T(b)).$$

5. The data storage device as recited in claim **4**, where:

$$\sigma_1^2(b) = E(n_{k-1,i}^2(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n_{k-1,t}(b)n(b)) -$$

-continued

$$\frac{[E(n_{k-1,t}(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n(b))]^2}{1 - E^T(n(b))R^{-1}(b)E(n(b))}$$
$$\sigma_2^2(b) = E(n_{k,i}^2(b)) - E^T(n_{k,t}(b)n(b))R^{-1}(b)E(n_{k,t}(b)n(b)) -$$
$$\frac{[E(n_{k,t}(b)) - E^T(n_{k,t}(b)n(b))R^{-1}(b)E(n(b))]^2}{1 - E^T(n(b))R^{-1}(b)E(n(b))}.$$

6. The data storage device as recited in claim **5**, where the control circuitry is further configured to compute a covariance matrix of the form:

$$\Sigma(b) = \begin{bmatrix} \sigma_1^2(b) & E(e_{k-1,t}(b)e_{k,t}(b)) \\ E(e_{k,t}(b)e_{k-1,t}(b)) & \sigma_2^2(b) \end{bmatrix}.$$

7. The data storage device as recited in claim **5**, where the control circuitry is further configured to generate a branch metric br of the 2D sequence detector according to:

$$br = -1n(|\Sigma(b)|) - e_t^T\Sigma^{-1}(b)e_t$$

where $e_t = [e_{k-1,t}(b), e_{k,t}(b)]^T$.

8. The data storage device as recited in claim **1**, wherein:
the first 2D DDNW filter is configured to minimize a first data dependent noise prediction error $e_{k-1,t}(b)$ based on:

$$e_{k-1,t}(b) = n_{k-1,t}(b) - \overline{A}_1^T(b)\overline{n}(b) - m_1(b)$$

the second 2D DDNW filter is configured to minimize a second data dependent noise prediction error $e_{k,t}(b)$ based on:

$$e_{k,t}(b) = n_{k,t}(b) - \overline{A}_2^T(b)\overline{n}(b) - m_2(b)$$

where:
t represents a time index;
b represents one of a plurality of data patterns;
$\overline{n}(b) = [n(b), 1]$
n(b) represents a 2D vector of past noise samples in the first and second 2D equalized samples;
$n_{k-1,t}(b)$ represents a noise sample in the first 2D equalized samples;
$\overline{A}_1(b) = [A_1(b), m_1(b)]$;
$A_1(b)$ represents a first data dependent noise prediction filter;
$m_1(b)$ represents a DC component of predicted noise in the first 2D equalized samples;
$n_{k,t}(b)$ represents a noise sample in the second 2D equalized samples; and
$\overline{A}_2(b) = [A_2(b), m_2(b)]$;
$A_2(b)$ represents a second data dependent noise prediction filter; and
$m_2(b)$ represents a DC component of predicted noise in the second 2D equalized samples.

9. The data storage device as recited in claim **8**, where:

$$\overline{A}_1(b) = \overline{R}^{-1}(b)E(n_{k-1}(b)\overline{n}(b))R(b) = E(n(b)n^T(b));$$

and

$$\overline{R}(b) = E(\overline{n}(b)\overline{n}^T(b)).$$

10. The data storage device as recited in claim **9**, where:

$$\overline{A}_2(b) = \overline{R}^{-1}(b)E(n_k(b)\overline{n}(b));$$

and

$$\overline{R}(b) = E(\overline{n}(b)\overline{n}^T(b)).$$

11. The data storage device as recited in claim **9**, where:

$$\sigma_1^2(b)=E(n_{k-1,t}^2(b))-E^T(n_{k-1,t}(b)\bar{n}(b))\bar{R}^{-1}(b)E(n_{k-1,t}(b)\bar{n}(b));$$

and

$$\sigma_2^2(b)=E(n_{k,t}^2(b))-E^T(n_{k,t}(b)\bar{n}(b))\bar{R}^{-1}(b)E(n_{k,t}(b)\bar{n}(b)).$$

12. The data storage device as recited in claim **11**, where the control circuitry is further configured to compute a covariance matrix of the form:

$$\Sigma(b) = \begin{bmatrix} \sigma_1^2(b) & E(e_{k-1,t}(b)e_{k,t}(b)) \\ E(e_{k,t}(b)e_{k-1,t}(b)) & \sigma_2^2(b) \end{bmatrix}.$$

13. The data storage device as recited in claim **12**, where the control circuitry is further configured to generate a branch metric by br of the 2D sequence detector according to:

$$br=-1n(|\Sigma(b)|)-e_t^T\Sigma^{-1}(b)e_t$$

where $e_t=[e_{k-1,t}(b), e_{k,t}(b)]^T$.

14. A method of operating a disk drive, the method comprising:

positioning a first read element over a first data track k−1 and position a second read element over a second data track k;

sampling a first read signal from the first read element to generate first signal samples;

sampling a second read signal from the second read element to generate second signal samples;

performing first 2D equalization of the first signal samples and the second signal samples to generate first 2D equalized samples;

performing second 2D equalization of the first signal samples and the second signal samples to generate second 2D equalized samples;

performing first 2D data dependent noise whitening (DDNW) filtering of the first and second 2D equalized samples to generate first 2D noise whitened samples;

performing second 2D DDNW filtering of the first and second 2D equalized samples to generate second 2D noise whitened samples; and

using a 2D sequence detector to detect a first data sequence recorded in the first data track from the first and second 2D noise whitened samples and to detect a second data sequence recorded in the second data track from the first and second 2D noise whitened samples.

15. The method as recited in claim **14**, wherein:

the first 2D DDNW filter is configured to minimize a first data dependent noise prediction error $e_{k-1,t}(b)$ based on:

$$e_{k-1,t}(b)=n_{k-1,t}(b)-A_1^T(b)n(b)-m_1(b)$$

the second 2D DDNW filter is configured to minimize a second data dependent noise prediction error $e_{k,t}(b)$ based on:

$$e_{k,t}(b)=n_{k,t}(b)-A_2^T(b)n(b)-m_2(b)$$

where:

t represents a time index;

b represents one of a plurality of data patterns;

n(b) represents a 2D vector of past noise samples in the first and second 2D equalized samples;

$n_{k-1,t}(b)$ represents a noise sample in the first 2D equalized samples;

$A_1(b)$ represents a first data dependent noise prediction filter;

$m_1(b)$ represents a DC component of predicted noise in the first 2D equalized samples;

$n_{k,t}(b)$ represents a noise sample in the second 2D equalized samples;

$A_2(b)$ represents a second data dependent noise prediction filter; and

$m_2(b)$ represents a DC component of predicted noise in the second 2D equalized samples.

16. The method as recited in claim **15**, where:

$$m_1(b)=[E(n_{k-1,t}(b))-E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n(b))][1-E^T(n(b))R^{-1}(b)E(n(b))]^{-1}$$

$$A_1(b)=R^1(b)[E(n_{k-1,t}(b)n(b))-m_1(b)E(n(b))]$$

$$R(b)=E(n(b)n^T(b)).$$

17. The method as recited in claim **16**, where:

$$m_2(b)=[E(n_{k,t}(b))-E^T(n_{k,t}(b)n(b))R^{-1}(b)E(n(b))][1-E^T(n(b))R^{-1}(b)E(n(b))]^{-1}$$

$$A_2(b)=R^1(b)[E(n_{k,t}(b)n(b))-m_2(b)E(n(b))]$$

$$R(b)=E(n(b)n^T(b)).$$

18. The method as recited in claim **17**, where:

$$\sigma_1^2(b) = E(n_{k-1,i}^2(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n_{k-1,t}(b)n(b)) - \frac{[E(n_{k-1,t}(b)) - E^T(n_{k-1,t}(b)n(b))R^{-1}(b)E(n(b))]^2}{1 - E^T(n(b))R^{-1}(b)E(n(b))}$$

$$\sigma_2^2(b) = E(n_{k,i}^2(b)) - E^T(n_{k,t}(b)n(b))R^{-1}(b)E(n_{k,t}(b)n(b)) - \frac{[E(n_{k,t}(b)) - E^T(n_{k,t}(b)n(b))R^{-1}(b)E(n(b))]^2}{1 - E^T(n(b))R^{-1}(b)E(n(b))}.$$

19. The method as recited in claim **18**, further comprising computing a covariance matrix of the form:

$$\Sigma(b) = \begin{bmatrix} \sigma_1^2(b) & E(e_{k-1,t}(b)e_{k,t}(b)) \\ E(e_{k,t}(b)e_{k-1,t}(b)) & \sigma_2^2(b) \end{bmatrix}.$$

20. The method as recited in claim **18**, further comprising generating a branch metric br of the 2D sequence detector according to:

$$br=-1n(|\Sigma(b)|)-e_t^T\Sigma^{-1}(b)e_t$$

where $e_t=[e_{k-1,t}(b), e_{k,t}(b)]^T$.

21. The method as recited in claim **14**, wherein:

the first 2D DDNW filtering minimizes a first data dependent noise prediction error $e_{k-1,t}(b)$ based on:

$$e_{k-1,t}(b)=n_{k-1,t}(b)-\bar{A}_1^T(b)\bar{n}(b)-m_1(b)$$

the second 2D DDNW filtering minimizes a second data dependent noise prediction error $e_{k,t}(b)$ based on:

$$e_{k,t}(b)=n_{k,t}(b)-\bar{A}_2^T(b)\bar{n}(b)-m_2(b)$$

where:

t represents a time index;

b represents one of a plurality of data patterns;

$\bar{n}(b)=[n(b), 1]$

n(b) represents a 2D vector of past noise samples in the first and second 2D equalized samples;

$n_{k-1,t}(b)$ represents a noise sample in the first 2D equalized samples;

$\bar{A}_1(b)=[A_1(b), m_1(b)];$

$A_1(b)$ represents a first data dependent noise prediction filter;

$m_1(b)$ represents a DC component of predicted noise in the first 2D equalized samples;

$n_{k,t}(b)$ represents a noise sample in the second signal samples; and

$\overline{A}_2(b)=[A_2(b), m_2(b)]$;

$A_2(b)$ represents a second data dependent noise prediction filter; and

$m_2 b$ represents a DC component of predicted noise in the second 2D equalized samples.

22. The method as recited in claim **21**, where:

$$\overline{A}_1(b)=\overline{R}^{-1}(b)E(n_{k-1}(b)\overline{n}(b))R(b)=E(n(b)n^T(b));$$

and

$$\overline{R}(b)=E(\overline{n}(b)\overline{n}^T(b)).$$

23. The method as recited in claim **22**, where:

$$\overline{A}_2(b)=\overline{R}^{-1}(b)E(n_k(b)\overline{n}(b));$$

and

$$\overline{R}(b)=E(\overline{n}(b)\overline{n}^T(b)).$$

24. The method as recited in claim **23**, where:

$$\sigma_1^2(b)=E(n_{k-1,t}^2(b))-E^T(n_{k-1,t}(b)\overline{n}(b))\overline{R}^{-1}(b)E(n_{k-1,t}(b)\overline{n}(b));$$

and

$$\sigma_2^2(b)=E(n_{k,t}^2(b))-E^T(n_{k,t}(b)\overline{n}(b))\overline{R}^{-1}(b)E(n_{k,t}(b)\overline{n}(b)).$$

25. The method as recited in claim **24**, further comprising computing a covariance matrix of the form:

$$\Sigma(b) = \begin{bmatrix} \sigma_1^2(b) & E(e_{k-1,t}(b)e_{k,t}(b)) \\ E(e_{k,t}(b)e_{k-1,t}(b)) & \sigma_2^2(b) \end{bmatrix}.$$

26. The method as recited in claim **25**, further comprising generating a branch metric br of the 2D sequence detector according to:

$$br=-1n(|\Sigma(b)|)-e_t^T\Sigma^{-1}(b)i\,e_t$$

where $e_t=[e_{k-1,t}(b), e_{k,t}(b)]^T$.

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